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Structural Controls of High-Temperature and Deep Geothermal Systems Associated with Detachment Fault

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ABSTRACT

In this study, the structural controls of a high-temperature system (188 to 287 °C) associated with the detachment fault in Gediz Graben generating approximately half of this electricity generation in Turkey which is in the top five of the world in the generation of electricity from geothermal resources are examined. The high-temperature geothermal reservoirs associated with detachment fault in the study area have formed along the normal faults nearly in E-W orientation and in intensely fractured rocks in a structurally complex manner associated with transfer faults approximately in N-S orientation. Generally, it has been determined that the reservoirs are closely located to strike-slip faults intersecting, overlapping, and/or terminated with Quaternary transfer faults. The same results as this study have also presented in the studies performed in western Anatolia and some regions of the world. Since the detachment fault and the high-angle normal faults cutting the detachment fault form the paths, this mechanism ensures that the geothermal fluids are drained from the surface to the reservoir rock environment. High-angle normal faults cutting the detachment fault and the transfer faults cutting the detachment-high-angle normal faults constitute the carrier systems. This causes that the fluids heated in the reservoir rock environment at the depths are carried to the surface. Therefore, transfer faults control the position of high-temperature geothermal systems and should be used as the primary guide for geothermal exploration.

1. INTRODUCTION

The first geothermal activities in Gediz Graben in Western Anatolia started in the 1960s due to high-temperature hot springs (Figure 1). In recent years, geothermal fluids have been produced up to 287 °C. Geothermal resources are used in regional and greenhouse heating, chemical production, tourism, health facilities, and mainly in electricity production [1-8]. The installed geothermal power capacity of Turkey reached 1668 MWe in 2020. There are more than 200 deep geothermal wells in the Gediz Graben. Numerous geothermal power plants are currently operating, and approximately 500 MW of electricity is generated from these power plants [9-17].

The high-temperature Kavaklıdere Geothermal Field (Alaşehir) is located along the active southern margin of the Gediz Graben (Figure 1). It is noteworthy that high-temperature geothermal fields in Western Anatolia are lined up along detachment faults on the edges of Büyük Menderes and Gediz grabens (Figure 1). This situation creates a need to investigate the role of a detachment fault in the occurrence of high-temperature geothermal systems (is detachment fault a channel for geothermal fluids or a physical mechanism that increases the geothermal gradient by generating frictional heat?). Therefore, in this study, structural controls in the Kavaklıdere field, a high-temperature field associated with the Gediz detachment fault, are investigated. The temperatures of geothermal reservoirs in the field range from 188 to 287 °C. The field contains numerous geothermal reservoirs in intersection areas with N-NNE trending transfer faults and the Gediz Detachment Fault [2-4, 8]. The main research focus of this study is to survey the structural controls of a high-temperature geothermal field related to the detachment fault.

2. GEOLOGICAL SETTING

Aegean extensional province occurs above the north-dipping Hellenic subduction zone in Africa-Eurasia convergent boundary in the Eastern Mediterranean region. There are two sets of Cenozoic extensional grabens and sedimentary basins in and around the Menderes Massif: those with NNE-SSW-trending and filled with lower Miocene and younger siliciclastic, volcaniclastic, and volcanic rocks, and those ~E-

W-trending and filled mainly with siliciclastic rocks [18-21]. Most of these grabens are bounded by high-angle normal faults with strike-slip components [18, 21, 22]. These E-W-trending grabens and basins are bounded by normal faults dipping with high to moderate-angles, some of which are seismically active [23-26], and destroying and crosscutting NNE-SSW-trending grabens and basins.

[18] reported that NNE-trending grabens locally occur as 'hanging grabens' in the E-W trending ones' footwalls and that the trapped structures and sedimentary units of these older NNE-trending grabens are distinguishable in the seismic profiles. 2D gravity and magnetotelluric (MT) modeling of the Gediz Graben's structure has revealed the existence of a series of these NE- trending grabens are distinguishable in the seismic profiles. 2D gravity and magnetotelluric (MT) modeling of the Gediz Graben's structure has revealed the existence of a series of these NE-SW-trending grabens and sub-basins at deeper depths [3, 4, 26, 27]. It also indicates that the regional structural fabric seen at the surface continues beneath the Quaternary sedimentary fill of the E-W-trending modern graben system.

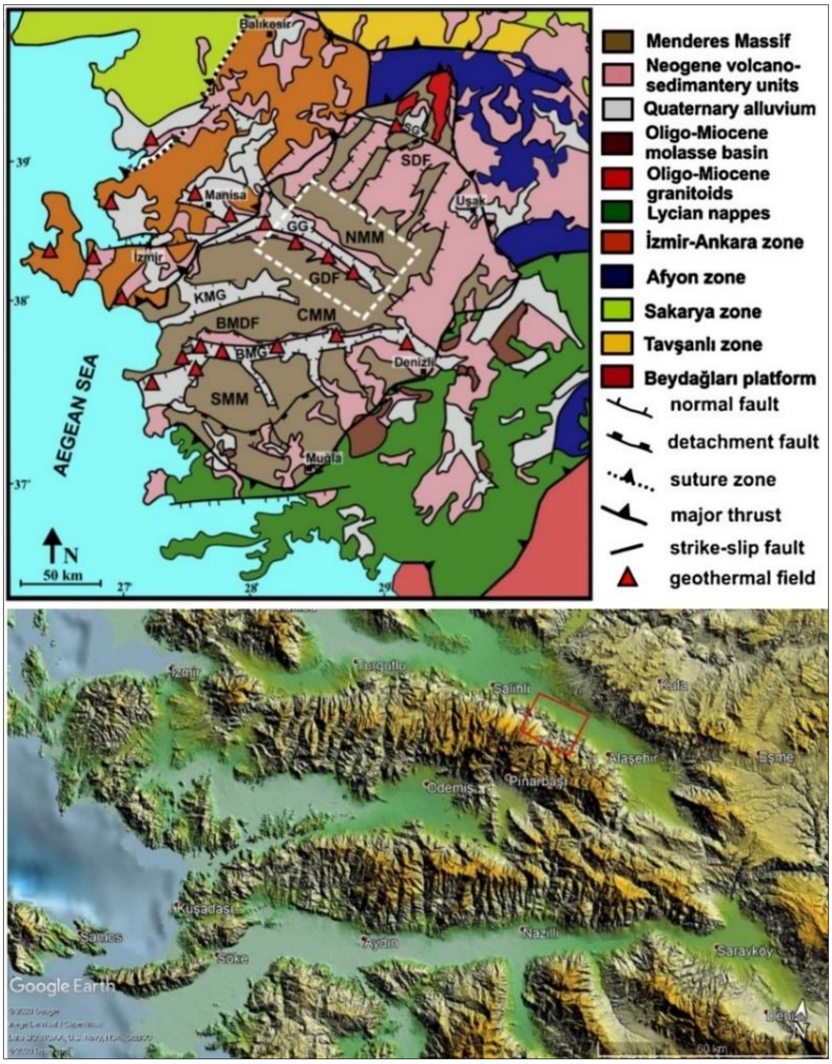

Figure 1. Location map of the study area. Main structures and grabens: NMM: Northern Menderes Massif, CMM: Central Menderes Massif, SMM: Southern Menderes Massif, BMG: Büyük Menderes Graben, GG: Gediz Graben, KMG: Küçük Menderes Graben, GDF: Gediz Detachment Fault, BMDF: Büyük Menderes Detachment Fault (the map is modified from **[5]**). The investigation area is marked on the map (red polygon).

Six different units have been determined in the investigation area. These units from bottom to top are as follows: (1) Metamorphic rocks (gneiss, calc-schist, quartz-schist, phyllite, mica-schist) of the Precambrian-Middle Triassic Menderes Massif (2) Paleozoic marbles (3) Granitic rocks (4) Upper Miocene-Lower Pliocene Gediz formation (5) Upper Pliocene-Quaternary sediments and Kaletepe formation (6) Quaternary alluviums, respectively (Figure 2) [2].

3. STRUCTURAL GEOLOGY

The study area is located within the Gediz Graben, extensional basin of 140 km in length, roughly E-W oriented and concaved southward, extending bein the north of Menderes massif. Normal faults border the graben from both margins (Figure 1). However, in this basin, that narrows in the eastern border, the western portion's morphologic boundaries are difficult to distinguish.

Dip-slip normal faults located in the south of the graben are intersected by NE-SW and NW-SE trending oblique and strike-slip faults in many places. The dip-slip normal faults prominently identified as detachment faults in the south have a listric faulting character. The detachment fault exhibits geometric features in the form of jumps. Transfer faults have developed in those stepping areas. The faults in the southern section of the graben are generally younger from the south to the north.

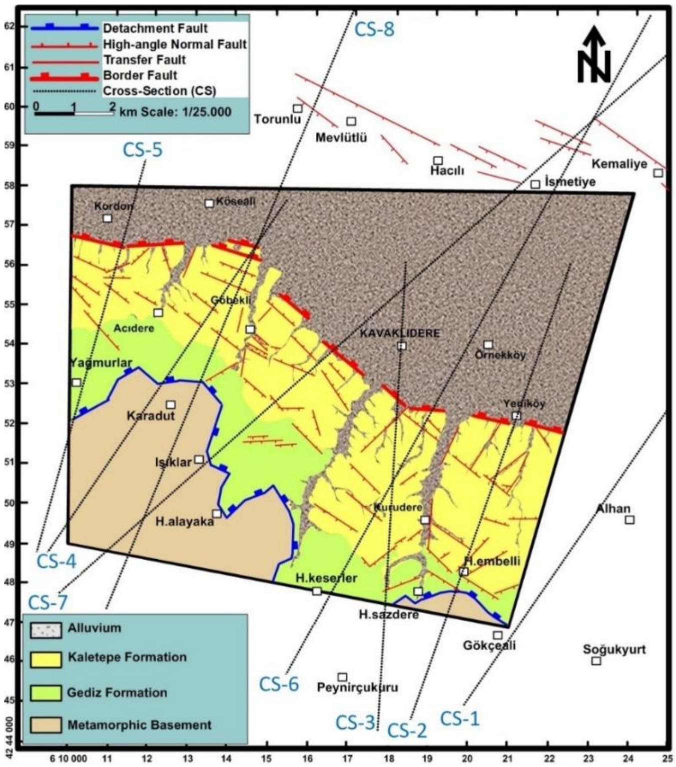

Figure 2. Simplified geological map and cross-section lines the study area (see Section 3.2 for cross-sections) (modified from [2]).

Metamorphics that constitute the highlands surrounding the graben from the south and north consist of gneiss, marbles, quartzites, and schists. Some of the faults bordering the graben formed contacts between the metamorphic basement rocks and Miocene, Pliocene, and Quaternary sediments. The Upper Miocene units are formed from conglomerates and sandstones outcropping at the margins of the graben. Pliocene units consist of dendritic sandstones and claystones, and the graben faults cut quaternary sediments.

Dips of fault planes of the normal faults in the investigation area located in the Gediz graben vary between 30° and 60°. To a certain degree, lower dips are measured. These faults are usually characterized by listric faulting. The layers are generally horizontal, and no folding has developed at the sediments between the fault blocks. On the other hand, the topographic surfaces of the footwall blocks sloped towards the hanging-wall blocks. It is known that the basement of the graben was downthrown by a minimum displacement of 1500 m after Pliocene [2].

The observations have been performed at 66 different stop points to explain the structural features of the region in which the study area is located and to reveal its faulting type, geometric properties, and faulting mechanism in detail. Faults with four different mechanisms are identified in the study area (Figure 2) [2]. These are;

• Detachment fault,
• Low-angle normal faults,
• High-angle normal faults,
• Transfer faults.

In light of the information obtained from the stop points (the stations), structural geological cross-sections of the study area have been prepared.

3.1. The Gediz Detachment Fault

The Gediz Detachment Fault bordering the study area from the south is remarkable, and the related detachment faults are generally NW-SE trending, nevertheless, they partially show different orientations. The detachment faults make the step to the right and left, and are dipped into the basin along with 20-30 degrees. Precambrian-Middle Triassic metamorphic rocks are juxtaposed with Upper Miocene-Lower Pliocene Gediz formation along the detachment fault. The detachment fault with mylonitic and breccia characteristics formed a large zone of 100-150 m in width (Figure 3). The upper parts of the metamorphic units were completely altered along the detachment fault zone and gained breccia characteristics. The eastern half of the study area contains breccia-mylonitic mica-schists/phyllites and marbles above the detachment fault zone, and the western part includes quartz-schists and calc-schists.

The detachment fault has a 100-150 m thick mylonitic-brecciated zone (the reservoir in the geothermal field). Completely disintegrated brecciated marbles are located at the upper levels of this zone (Figure 3). There is an elevation difference of approximately 3000 m between the detachment fault and the basin plane.

The juxtaposition of the Gediz formation to the metamorphic units along the detachment fault zone indicates that the detachment fault may have been formed during or after the occurrence of the Gediz formation. This opinion is supported by the fact that the base levels of the Gediz formation are highly deformed. The strata are tilted towards the detachment fault, and the Gediz formation contains low-angle normal faults.

A great number of NW-SE trending high-angle normal faults intersecting the Gediz and Kaletepe formations are developed on the hanging wall of the detachment fault. Partly, NE-SW trending dip-slip normal faults exist as well. It is foreseen that the high-angle normal faults intersect and displace the detachment faults at the depths. It is also observed that the high-angle normal faults in the areas close to the detachment fault dip towards SW while the faults in the areas close to the basin do towards NE. The differences in the dip directions have caused the formation of mini-grabens on the downthrown block of the detachment fault and the formation of a horst-shaped area between the aforementioned grabens. By the way, the listric character of the detachment fault has

EUROPEAN JOURNAL OF TECHNIQUE, Vol.12, No.1, 2022

contributed to the shape of an asymmetric graben currently observed in the basin.

Figure 3. Views from the detachment fault and breccia zone (the reservoir formation observed in the study area).

3.2. Geological cross-sections

Based on the findings from the geological and tectonic field studies carried out and the estimated total fault displacements in the area, eight geological cross-sections have been taken in NW-SW (3 of them) and NE-SW (3 of them) directions in the study area (Figure 2). It is estimated that the total displacement of the normal faults, which bounds the study area from the south, is about 1500-2000 m. This total displacement is considered in each geological cross-section.

To find an answer to questions:
(1) how the detachment fault in the study area extends geometrically from south to north to the basin,
(2) how the high-angle normal faults affect the detachment fault at the depths,
(3) how the thickness of the sediments in the basin reached up to 2000 meters.

The detailed interpretations of the geological cross-sections taken for the study area are performed below.

15 km long-cross-section 1 (CS-1) in NE-SW direction extends along Alhan creek between Gökçealan in the SW and Piyadeler in the NE, from a part close to the SW corner of the study area (Figures 2 and 4). As it is clearly seen in Cross-section 1, the detachment fault exposes in the SW. However, it reaches the deeper areas being cutting and making offset by the high-angle normal faults towards into the basin to the NE. The detachment fault has a listric character.

The metamorphic units juxtapose with Gediz formation along the detachment fault in the SW. Displacements of the high-angle normal faults increase towards the NE from the SW. As a result of vertical displacements, the thicknesses of Gediz and Kaletepe formations increase to continue towards the NE from the SW and reach the maximum values in the basin. These phenomena point out that the high-angle normal faults have been active in the area until today since the occurrence of the detachment fault. There is an elevation difference of approximately 850 m between the detachment fault and the basin plain.

15 km long-cross-section 2 (CS-2) in NE-SW direction, close to the eastern border of the study area, extends between Gökçealan in NE and Yeniköy in GB, and is parallel to the east edge of the Hacıahmet creek (Figures 2 and 5).

As seen in cross-section 2, the detachment fault deepens towards the NE from the SW. However, in the northern of Yeniköy, it is displaced downwards up to 1500-2000 m at the hanging-wall block. Unlike this cross-section, several antithetic stepping faults dipped towards the detachment fault are located. In other words, the faults dipped towards the SW and the area between the detachment fault and the basin are uplifted.

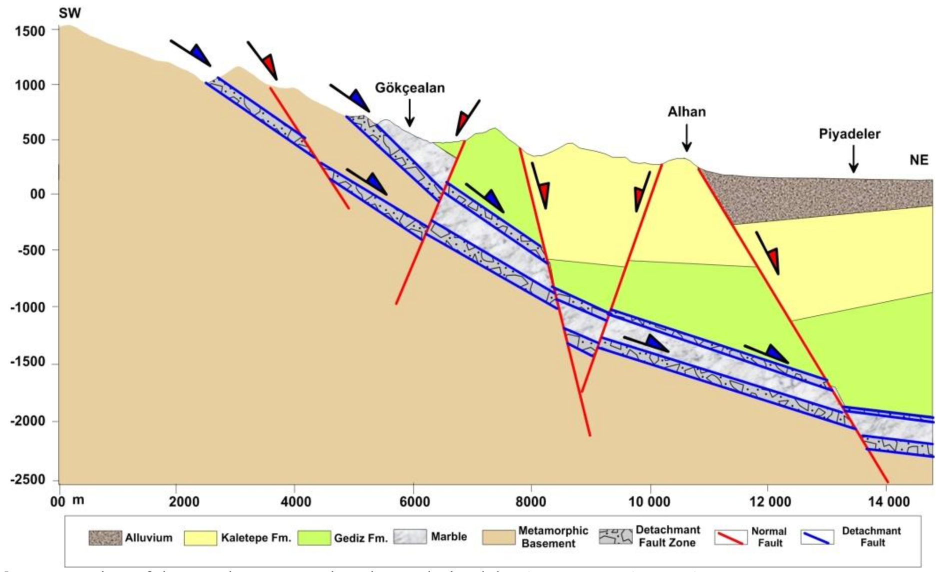

Figure 4. Geological cross-section of the area between Gökçealan and Piyadeler (CS-1, see **Figure 2**).

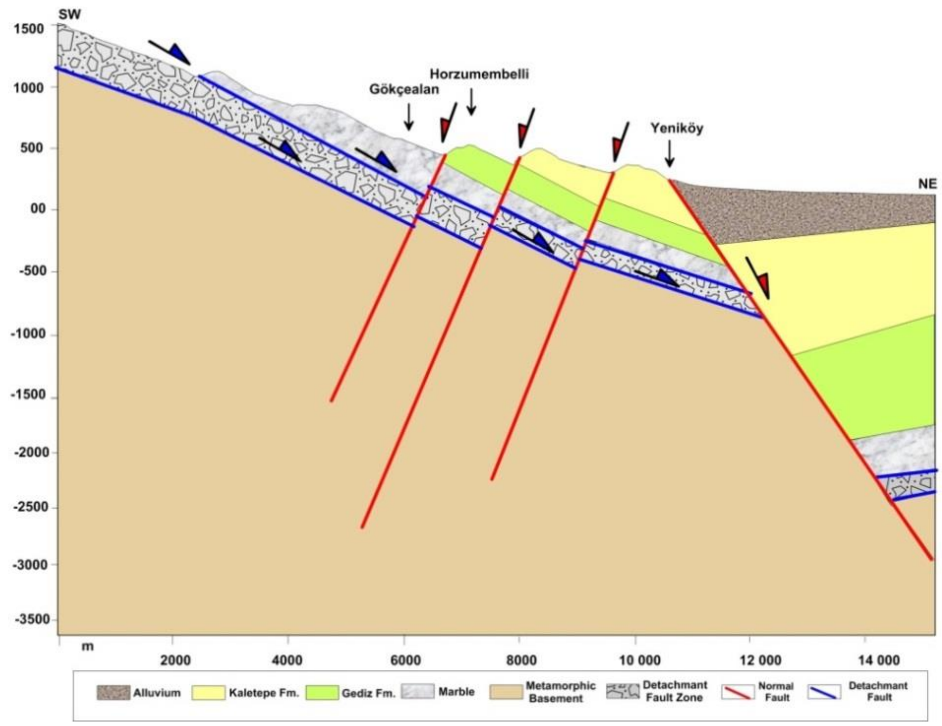

Figure 5. Geological cross-section of the area between Gökçealan and Yeniköy (CS-2, see **Figure 2**).

15 km long-cross-section 3 (CS-3) in N-S direction extends between Peynirçukuru village in the SW and Kavaklıdere in the NE, close to the center of the study area (Figures 2 and 6).

Cross-section 3 has a structure similar to Cross-sections 1 and 2. The detachment fault continues by deepening and uplifting towards the north, so it is downthrown up to 1500-2000 m by the main fault.

There is a thick and brecciated marble zone above the detachment fault. The high-angle normal faults dip towards the detachment fault in the south and towards the basin side in the north. As a result of the dipping towards the SW and NE, a subsidence is occurred towards the detachment fault's side. An elevation difference of approximately 800 m is present between the detachment fault and the basin plain.

15 km long-cross-section 4 (CS-4) in N-S direction extends between Karadut village in the SW and Köseali in the NE. It is parallel to the western edge of the Göbekli stream, close to the west side of the study area (Figures 2 and 7). While the detachment fault continues into the deep and is vertically displaced towards the northeast, it is displaced up to 1500-2000 m downward by the border (main) fault. Brecciated quartz schists overlie the detachment fault.

On the hanging wall of detachment fault, continuous depression is occurred towards the basin as a result of a series of stepping faults dipped to the NE towards the north apart from the antithetic faulting dipping towards the SW. However, the most extensive subsidence and deposition area has been occurred. There is an elevation difference of approximately 400 m between the detachment fault and the basin plain in the vicinity of Karadut and 1300 m with the part behind it.

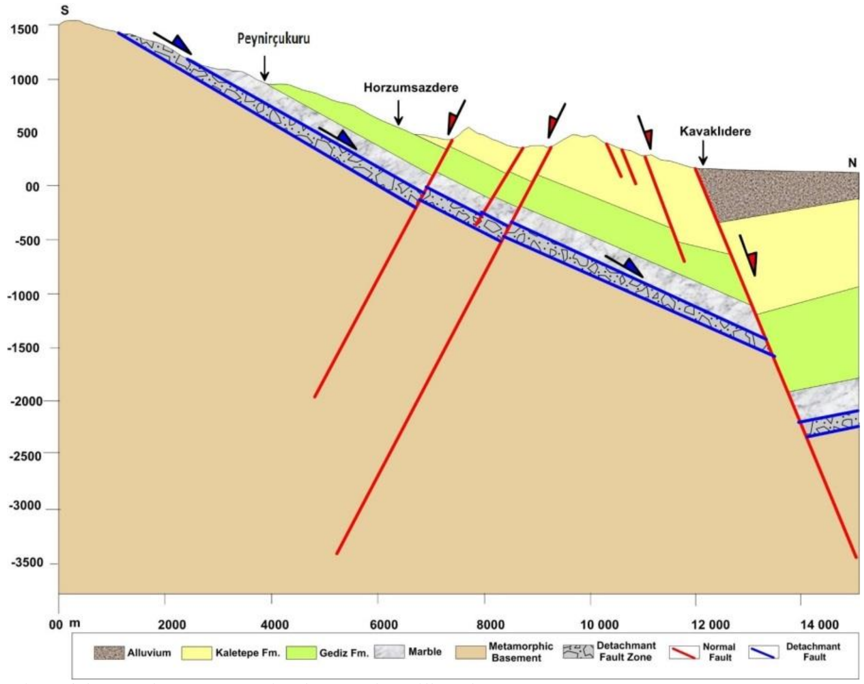

Figure 6. Geological cross-section of the area between Peynirçukuru and Yeşilkavak (CS-3, see **Figure 2**).

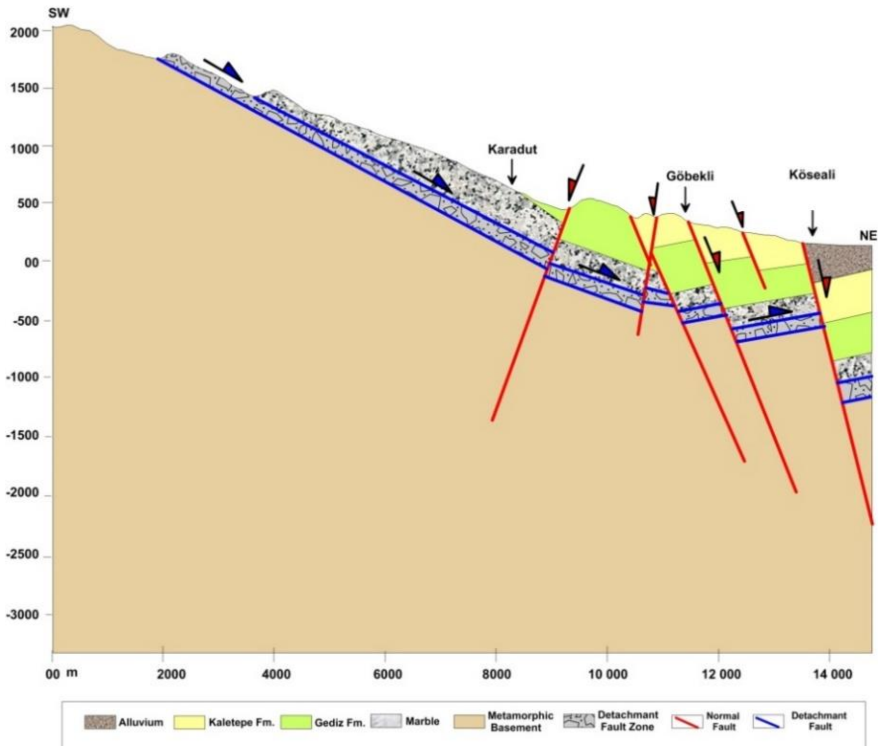

Figure 7. Geological cross-section of the area between Karadut and Köseali (CS-4, see **Figure 2**).

13 km long-cross-section 5 (CS-5) in NNE-SSW direction extends between Yağmurlar village in the SW and Kordon in the NE (Figures 2 and 8). It has a structure that is very similar to the cross-section 4. Brecciated calc-schists are exposed above the detachment fault.

As a consequence of the antithetic faulting dipped towards the SW in front of the detachment fault, a depression occurs between the detachment fault and antithetic faults and an uplifting area in the north of the detachment fault. Continuous subsided areas develop towards the basin. There is an elevation difference of approximately 450 m between the detachment fault and the basin plain in the vicinity of Yağmurlar and 1000 m behind it.

35 km long-cross-section 6 (CS-6) in NE-SW direction extends between Karadağ village in the SW and İsmetiye in the NE, on the eastern side of the study area (Figures 2 and 9).

The detachment fault becomes listric faulting towards the basin depths from the SW to the NE and deepens by vertical displacement of the high-angle faults. It is downthrown approximately 1500-2000 m by the main fault bordering the basin from the south. It is anticipated that the antithetic faults border the basin from the north and dipped towards the SW.

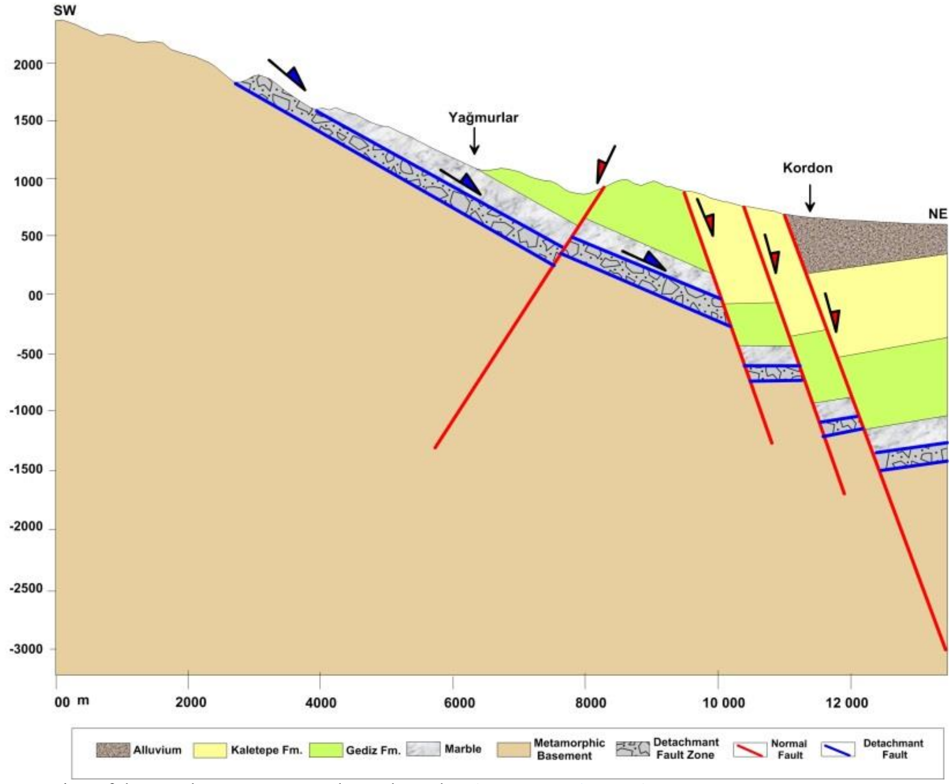

Figure 8. Geological cross-section of the area between Yağmurlar and Kordon (CS-5, see **Figure 2**).

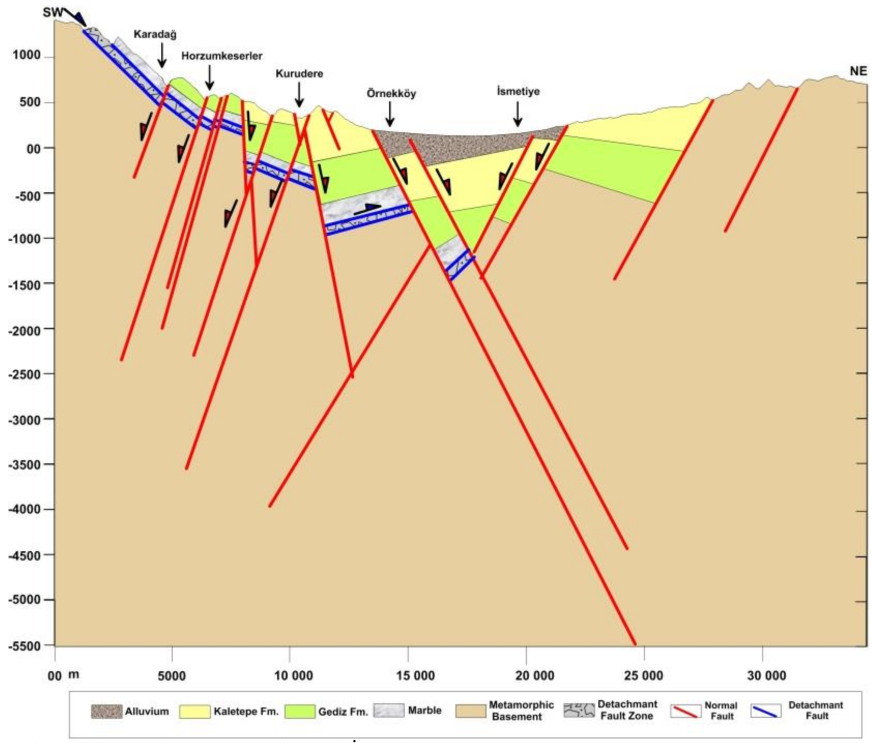

Figure 9. Geological cross-section of the area between Karadağ and İsmetiye (CS-6, see **Figure 2**).

The high-angle normal faults between the detachment fault and Kurudere dip towards the SW. However, this bordering from the south of the basin in Kurudere has a dip towards the NE. Because of the high-angle normal faults dipping towards the SW and NE, mini horst and graben areas are developed between the detachment fault and the basin. In this section, there is an elevation difference of 800 m between the SW and NE of the basin and 650 m between the detachment fault and the basin plain. Depending on the total displacement of the high-angle normal faults, the thicknesses of alluvium at the bottom of the basin, Kaletepe formation, and Gediz formation reach the maximum level. As the detachment fault progresses towards from the basin, the thickness relatively decreases.

32 km long-cross-section 7 (CS-7) in NE-SW direction, which is towards the NE corner from the SW corner of the study area, extends between Işıklar village in the SW and İsmetiye in the NE (Figures 2 and 10).

The detachment fault becomes listric towards the basin from the SW to the NE in depth similar to the structure in the Cross-section 6 and deepens by being displaced by the high-angle faults. It is predicted that the total displacement of the main fault bordering from the south of the basin is about 1500-2000 m.

EUROPEAN JOURNAL OF TECHNIQUE, Vol.12, No.1, 2022

Unlike Cross-section 6, the detachment fault continues towards the NE of the basin. It is cut and displaced by the antithetic faults which border the basin from the north and dip towards the SW. Furthermore, the high-angle normal faults have a stepping faulting character and dip to the basin towards the NE. It is assumed that the detachment fault is located in the metamorphic basement at the depths. In other words, the basin margin has been continuously downthrown towards the NE from the SW. In this section, there is an elevation difference of 1200 m between the SW and NE of the basin and 450 m between the detachment fault and the basin plain.

27 km long-cross-section 8 (CS-8) in NE-SW direction extends between Karadut village in the SW and Mevlütlü in the NE, on the western side of the study area (Figures 2 and 11). Although the cross-section 8 is very similar to the faulting structure in the cross-section 7, the only difference is that the bottom of the detachment fault forms a mylonitic-breccia zone at the thickness of 100-150 meters, which consists of calcschists, under Gediz formation. In this section, there is an elevation difference of 600 m between the SW and NE of the basin and 200 m between the detachment fault and the basin plane.

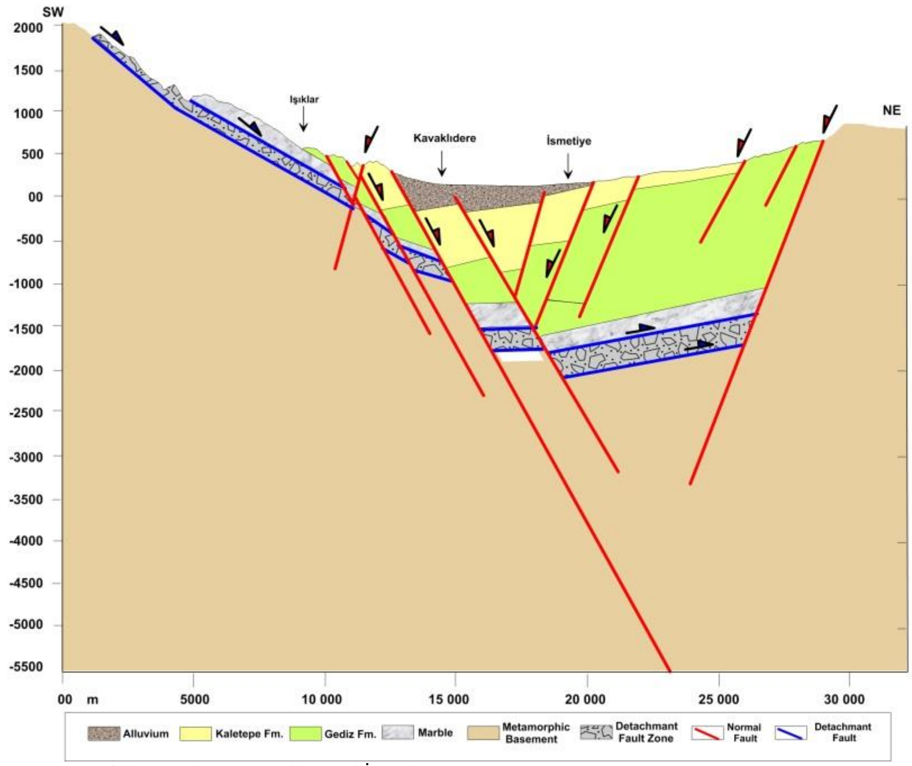

Figure 10. Geological cross-section of the area between Işıklar and İsmetiye (CS-7, see **Figure 2**).

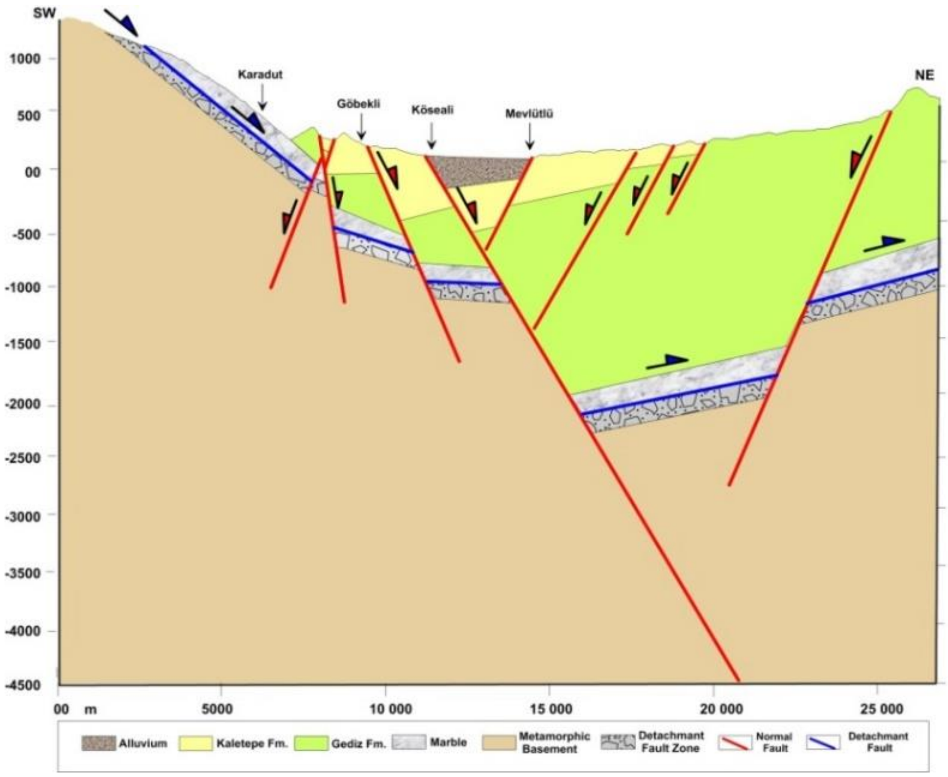

Figure 11. Geological cross-section of the area between Karadut and Mevlütlü (CS-8, see **Figure 2**).

EUROPEAN JOURNAL OF TECHNIQUE, Vol.12, No.1, 2022

3.3. Relationship between structural controls and high-temperature geothermal systems

Back-arc basins are known to be controlled by deep subduction dynamics. In the Aegean domain, the slab retreat led to the formation of crustal-scale low-angle normal faults (detachment faults) that were involved in the exhumation of Metamorphic Core-Complexes in this region. The detachment system in western Anatolia can be given as an example of these kinds of crustal-scale low-angle normal faults. These large-scale structures are associated with heat exchange and fluid circulations representing a major interest in understanding hydrothermal systems. The Menderes massif of western Anatolia is the location of active exploitation of high-temperature geothermal resources related to extension and the activity of the main detachments. However, the rock-fluid interactions in the deep part of the geothermal reservoir are not accessible to observation. The detachments are coeval with the emplacement of granitoids and associated with the formation of a supra-detachment sedimentary basin during the Late Miocene [28]. Young tectonism (Gediz detachment fault) and young volcanism (Salihli granitoid and/or Kula volcanism) in the study area have caused the occurrence of a high-temperature geothermal system [2, 8].

High-temperature geothermal resources aligned on both the northern and southern edges of detachment faults in western Anatolia demonstrate that the heating source is related to active tectonism (shear heating) rather than a magmatic origin [2, 29]. The highest heat flow values in western Anatolia have a remarkable perfect harmony with detachment faults. This indicates that detachment faults provide a channel in the fluid circulation and can be regarded as a possible source of heat [29]. The Menderes Province represents a favorable setting for amagmatic high-enthalpy geothermal resources. The origin of these systems' heat may be also related to a deeper source induced by subduction dynamics (i.e., magmatic underplating under the overriding plate) [5, 30-32].

The geothermal reservoir in the study area appears to lie on the intersections of northerly striking sinistral normal transfer faults and the Gediz detachment fault. Left steps in the transfer faults at the intersection with the detachment fault are represented dilational jogs that provide channel ways for geothermal fluids. The left steps may result from refraction across the detachment surface that asides from the mechanical contrast between hanging-wall sedimentary rocks and basement gneisses, marbles, and schists in the footwall. Brecciated marble zone (Figure 3) at these intersections provides suitable reservoirs for the accumulation of geothermal fluids. The geothermal reservoirs are plunged gently northward along the intersection of the detachment fault with the transfer faults. Although this model can account for the shallow reservoir and surface springs, it may not be appropriate to predict the location of the main upwelling that feeds these geothermal systems. Significant steps in the Alaşehir border (main) fault or complex fault intersections between the transverse faults and WNW-striking normal faults may accommodate upwelling in the study area (Figure 12).

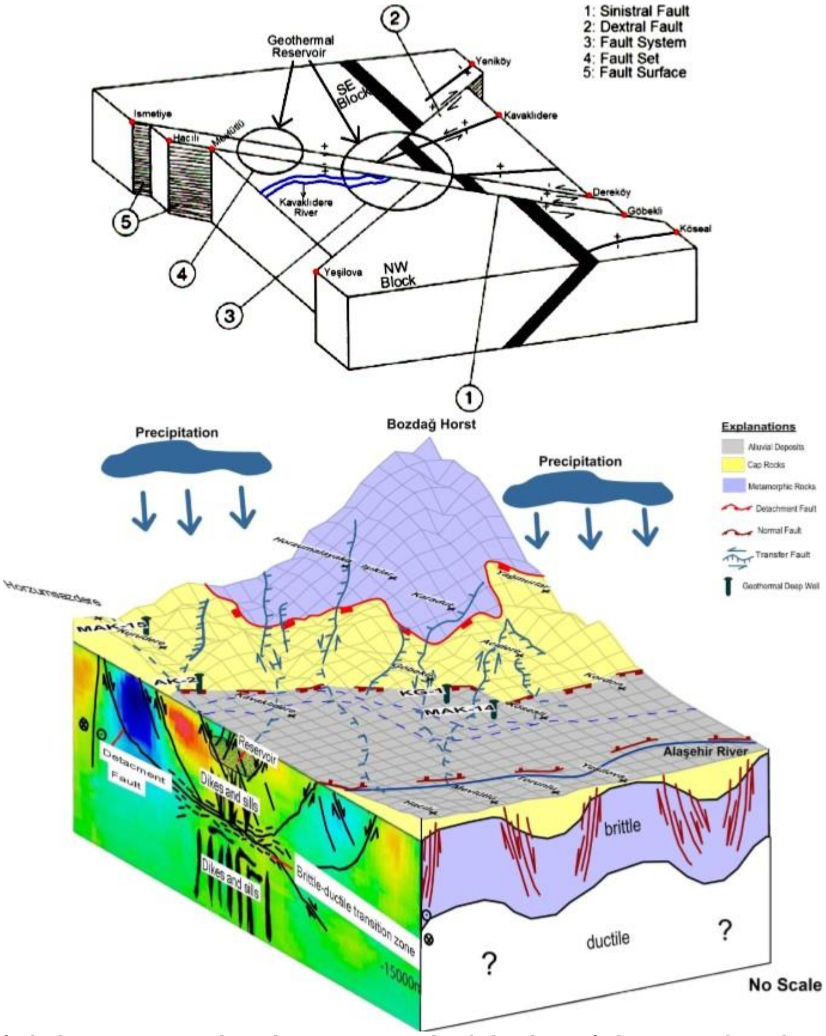

Figure 12. Conceptual models for high-temperature geothermal system associated with detachment fault system in the study area (modified from [2]).

The high-temperature geothermal reservoirs associated with detachment fault in the study area have formed along the normal faults nearly in E-W orientation and in intensely fractured rocks in a structurally complex manner associated with transfer faults approximately in N-S orientation. Generally, the high-temperature reservoirs are closely located to strike-slip faults intersecting, overlapping, and/or terminated with Quaternary transfer faults (oblique-slip hinge fault) (Figures 12 and 13). [33] emphasized the similar structural controls in the Kızıldere field, which is a high-temperature geothermal field associated with the Büyük Menderes Detachment Fault in western Anatolia. The same results as this study have also presented in the studies performed in western Anatolia and some regions of the world [31, 34-36].

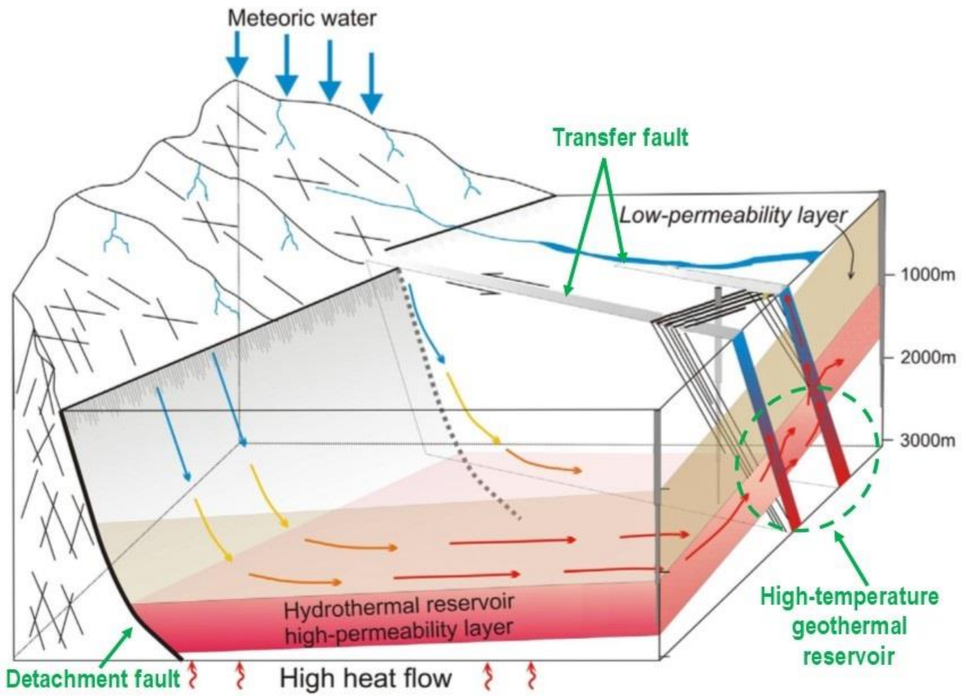

Figure 13. Schematic representation of a high-temperature geothermal reservoir formed at the intersection of the detachment fault and transfer fault (oblique-slip hinge fault) (modified from [35, 37].

4. CONCLUSIONS

High-temperature geothermal fields on Büyük Menderes and Gediz grabens' detachment faults show that these faults can be considered as one of the most potential areas in terms of research and exploration of high-temperature geothermal systems. Thus, in this study, to characterize the structural control of detachment, transfer, and dip-slip normal faults' association in the occurrence of high-temperature geothermal reservoirs, the main concentration has been on the determination of transfer faults and investigation of their relationships with detachment and dip-slip faults in high-temperature geothermal reservoir exploration activities associated with detachment fault in a detailed fashion. Since the detachment fault and the high-angle normal faults cutting the detachment fault form the paths, this mechanism ensures that the geothermal fluids are drained from the surface to the reservoir rock environment. High-angle normal faults cutting the detachment fault and the transfer faults cutting the detachment-high-angle normal faults constitute the carrier systems. This causes that the fluids heated in the reservoir rock environment at the depths are carried to the surface. Transfer faults control the position of high-temperature geothermal systems and should be used as the primary guide for geothermal exploration.

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